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RESTORING COASTAL HABITAT USING MARSH TERRACING: THE EFFECT OF CELL SIZE ON NEKTON USE

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Abstract: Marsh terracing is used to restore coastal wetlands by converting shallow nonvegetated bottom to intertidal marsh. Terraces are constructed from excavated bottom sediments, and are commonly arranged in a checkerboard pattern of square cells with open corners to form terrace fields. In 1999, terrace cells of three sizes (large = 122 m sides with 1.30 ha ponds; medium = 61 m sides with 0.29 ha ponds; small = 30 m sides with 0.06 ha ponds) were incorporated into a restoration project constructed at Galveston Island State Park, Texas, USA. This restoration project provided an opportunity to examine how nekton populations and the cost effectiveness of terracing projects vary with cell size. We compared nekton density and biomass (as measures of habitat value) in marsh and open water habitat types among the three cell sizes of the terrace fields. We also compared the habitat value of these terrace fields with the area before project construction, with nearby nonvegetated bottom, and with natural marsh habitat. Nekton abundance and biomass increased substantially in the project area following restoration by marsh terracing. An analysis of post-construction samples detected few statistically significant differences in animal density and biomass among cell sizes or between the terraced areas and adjacent natural habitats. Within terrace cells, density, biomass, and species richness were generally higher in marsh vegetation than over nonvegetated bottom. Using these post-construction density data, GIS, and population models for selected fishery species, we show that populations of most fishery species increase as cell size decreases. However, as cell size decreases, the cost of terrace construction increases much faster than population size. Therefore, terrace fields constructed of medium or large cells would be more cost effective in providing fishery habitat than would terraces composed of small cells.

Key Words: decapods, fishes, habitat, northern Gulf of Mexico, nursery areas, restoration, tidal marsh

INTRODUCTION

Marsh terracing is a relatively new habitat-restoration technique used to convert shallow subtidal bottom to intertidal wetlands (Underwood et al. 1991, Turner and Streever 2002). Terraces are constructed from excavated bottom sediments and are arranged in some pattern to form a terrace field. A common arrangement of terraces is a checkerboard pattern of square cells with open corners. Following construction, the intertidal area within a terrace field is planted with marsh vegetation.

We previously assessed the nursery value for fishery species of the original terracing project constructed in 1991 at Sabine National Wildlife Refuge (SNWR), Louisiana (Rozas and Minello 2001). That study showed that in a mesohaline estuarine system, terrace marsh supported higher densities of some fishery species (e.g., brown shrimp *Farfantepenaeus aztecus* (Ives) and blue crab *Callinectes sapidus* Rathbun) compared with terrace ponds. We concluded that the habitat value of a terrace field would increase as the proportion of emergent marsh increased.

One way to increase marsh area would be to reduce the size of each cell (relative to the SNWR design) within the terrace field. Rozas et al. (2005a) used a modeling approach to examine the effect of cell size on selected fishery species, but the effect of cell size on habitat value has not been examined

directly. Reducing cell size would increase both the density of terraces and the amount of edge vegetation in the terrace field; thus, the abundance of fishery species that use marsh edge habitat should increase (Zimmerman et al. 1984, Baltz et al. 1993, Peterson and Turner 1994). Decreasing cell size also should reduce fetch within the cells, promote sedimentation, and reduce turbidity (Underwood et al. 1991, Steyer 1993). However, reducing cell size may negatively affect fishery habitat by increasing the percentage of disturbed bay bottom in each terrace cell. In addition, the more complex patterns of connectivity within a terrace field composed of small cells may reduce access for transient organisms. Of course, decreasing cell size will increase the construction cost per unit area of a terrace field (Rozas et al. 2005a).

Galveston Island State Park (GISP) is in a polyhaline region of the lower Galveston Bay system, and has been subjected to high relative rates of sea level rise over the last 50 years (White et al. 1993, 2004). Coupled with shoreline erosion, these conditions have resulted in a dramatic loss of salt marsh in the park. For example, when the park was established in the 1960s, it contained 364 ha of salt marsh; by the mid 1990s, only 40 ha of salt marsh remained. To counter this habitat loss, a multiagency cooperative restoration plan was developed in 1997 to restore intertidal and shallow subtidal habitat at GISP using terracing.

More than 50 ha of terrace fields have been created in GISP thus far, and plans call for constructing additional terraces as more funds become available. Terrace construction in the initial fields was completed in spring and summer of 1999, and that summer the terrace ridges were planted with *Spartina alterniflor*a Loisel. These terrace fields were designed to include cells of three sizes, and to provide an opportunity to assess the effect of cell size on fishery habitat quality.

Our goals were to evaluate marsh terracing as a method for restoring estuarine habitat and fishery production in Galveston Bay, and to test whether cell size affects the fishery value of habitat created by marsh terracing. Before terrace construction, we measured nekton (fishes and decapod crustaceans) use of the shallow nonvegetated bottom (NB) that was to be replaced by the terrace fields. Approximately 2–3 years after the terrace fields were built, we tested the effect of cell size on habitat value by comparing nekton use of marsh, shallow NB, and deep NB among the three cell sizes and an adjacent natural area. All comparisons were made from samples collected during spring (May) and fall (September or October), when high densities of fishery species are known to occur within estuaries

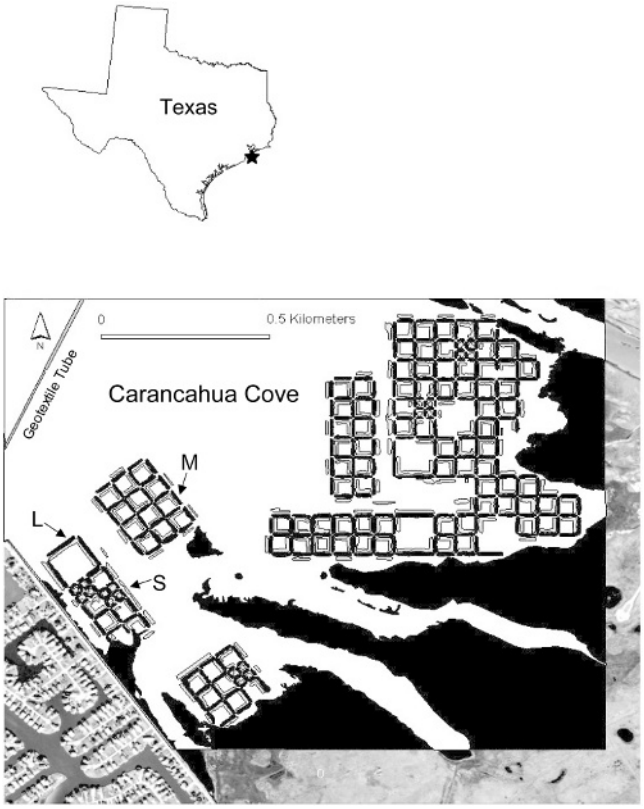

Figure 1. Map showing the study area within Carancahua Cove at Galveston Island State Park and its location on the Texas coast. Terrace fields incorporated small (S = 30 × 30 m), medium (M = 61 × 61 m), and large (L = 122 × 122 m) cells. The project area was protected from waves by a segmented geotextile tube that allowed tidal exchange between the cove and West Bay. Within the terrace fields: black represents vegetation, white represents shallow NB, and gray represents deep open water borrow areas.

of the northern Gulf of Mexico (Rakocinski et al. 1992, Livingston 1997, Akin et al. 2003). We also conducted a benefit-cost analysis of terracing that contrasted fishery benefits with construction costs to estimate optimal cell size.

MATERIALS AND METHODS

Our study area was located within GISP in Carancahua Cove (29°12′ N, 94°58′ W) on the upper Texas coast (Figure 1). Tides in the study area are predominantly diurnal and have a mean daily range of 0.3 m (Orlando et al. 1991).

We collected 10 pre-construction samples each during May and October 1998 on shallow nonvegetated bottom within the area designated for terrace construction. Sample sites were selected using random numbers and a grid placed over an aerial photograph of the area.

When the restoration plan was implemented in 1999, terrace cells of three sizes were constructed (Figure 1). Large cells (n = 5) were constructed with 122 m sides surrounding 1.30 ha ponds. A total of 100 medium cells had 61 m long sides, 0.29 ha ponds, and approximately one-fourth the area of large cells. These medium cells were equal in size to the original cells constructed in Louisiana (Underwood et al. 1991). Twenty small cells were constructed with 30 m sides, 0.06 ha ponds, and approximately one-fourth the area of medium cells.

In both September 2001 and May 2002, we collected 84 post-construction nekton samples. Seven randomly located sampling sites were selected within each of the 12 cell size treatment and habitat type combinations. The cell size treatment included the three cell sizes (small, medium, large) and the natural reference area outside the terrace fields. The habitat types included marsh edge (vegetated samples 1–2 m from shore), shallow (< 1 m) NB (undisturbed open water within terrace fields or the reference area), and deep (> 1 m) NB (borrow areas within terrace cells or naturally deep water within the reference area).

Nekton was quantitatively sampled using a 1-m^2 drop sampler as described by Zimmerman et al. (1984). Immediately after the drop sampler was deployed to enclose a sample area, we measured water temperature, dissolved oxygen, salinity, and turbidity using the methods described by Minello and Zimmerman (1992). We determined water depth at each sample site by averaging five measurements taken within the sampler. We also measured the distance from the center of the sampler to the nearest marsh edge. At marsh sites, stems of emergent vegetation were clipped at the ground level, counted, and removed from the sampler.

We removed the animals by using dip nets and filtering the water pumped out of the sampler through a 1-mm mesh net. When the sampler was completely drained, we removed by hand any animals remaining on the bottom. Samples were preserved in formalin and returned to the laboratory for processing.

In the laboratory, animals were separated from detritus and plant parts and identified to the lowest feasible taxon. Fishes and most crustaceans were identified using Heard (1982), Williams (1984), Abele and Kim (1986), Hoese and Moore (1998), McEachran and Fechhelm (1998), and Richards (2005). We used the nomenclature of Perez-Farfante and Kensley (1997) for penaeid shrimps and identified species using the protocol described in Rozas and Minello (1998). Specimens of penaeid shrimp (11% of total) that could not be reliably identified because of their size (13–18 mm total length *Farfantepenaeus*) or because they were damaged were classified based on the proportion of identified species in each sample. Unidentified grass shrimp (24% of total), *Callinectes* spp (< 1% of total), *Anchoa* spp (1% of total), and *Brevoortia* spp (< 1% of total) were similarly assigned to species. Animals that could not be readily identified were not used in size analyses. Total length of fishes and shrimps and carapace width of crabs were measured to the nearest mm. Individuals of a species in each sample were pooled to determine biomass (wet weight) to the nearest 0.1g.

Data Analyses

We compared nekton use of shallow NB before construction of the terrace fields with this same habitat in the reference area after terrace construction using t-tests. For the more extensive (i.e., more habitats) post-construction data, we used 2-way analysis of variance (ANOVA) followed by *a priori* contrasts to examine differences in nekton use among cell-size treatments and habitat types (an example is given in Table 1). The independent observations in these analyses included density, biomass, species richness, size of selected animals, and environmental variables. We made the following comparisons with *a priori* contrasts when we detected a significant treatment effect: 1) small cell vs. medium cell, 2) large cell vs. medium cell, and 3) small cell + medium cell + large cell vs. reference area. The first two contrasts compare means among terraces of different cell sizes, and the third contrast compares means in the terraces (all three cell sizes combined) to those in the reference area. When we detected a significant habitat type effect, we used the following *a priori* contrasts: 1) shallow NB vs. deep NB and 2) marsh vs. shallow NB + deep NB. The first contrast compared means within nonvegetated areas between shallow and deep sites. The second contrast compared marsh and nonvegetated open water sites.

We analyzed the data collected each season separately, because several species were only abundant enough to include in the statistical analysis for one season. We considered alpha levels of 0.05 to be statistically significant in all results, but we also assessed significance after adjusting alpha levels for the t-tests and the two main effects of the ANOVAs using the sequential Bonferroni method described by Rice (1989), which buffers against error introduced by making multiple comparisons with the same sample set (i.e., testing a hypothesis for multiple species or dependent variables). We present significance results in this manner because some readers may be interested

Table 1. Analysis of Variance (ANOVA) table for comparing three habitat types (Marsh Edge, Shallow and Deep Nonvegetated Bottom = NB) and four treatments (small, medium, and large cells and a reference area). Model includes tests for the main effects of Habitat Type and Treatment and *a priori* contrasts that compare specific levels within each factor. The dependent variable used in the example presented here is total macrofauna for September 2001.

SOURCE	df	SUM OF SQUARES	MEAN SQUARE	F VALUE	P VALUE
HABITAT TYPE	2	69.724	34.862	52.967	0.0001
CONTRASTS					
Shallow NB vs Deep NB	1	1.408	1.408	2.139	0.1479
Marsh vs Shallow NB + Deep NB	1	68.317	68.317	103.795	0.0001
TREATMENT	3	1.798	0.599	0.911	0.4403
CONTRASTS					
Small Cell vs Medium Cell	1	1.293	1.293	1.965	0.1653
Large Cell vs Medium Cell	1	0.001	0.001	0.002	0.9628
Small Cell + Medium Cell + Large Cell vs Reference Area	1	0.129	0.129	0.197	0.6588
HABITAT TYPE X TREATMENT	6	6.361	1.060	1.611	0.1566
RESIDUAL ERROR	72	47.389	0.658		

in only one or two statistical tests (e.g., one species), and the unadjusted significance values are appropriate for such comparisons. Mean densities and biomasses were positively related to the standard deviation; therefore, we did a ln (x + 1) transformation of the original values prior to analyses. Other variables were not transformed. All tabular and graphical data presented in this paper are untransformed means. We conducted statistical analyses using Super-ANOVA (Version 5 Ed., Abacus Concepts, Inc., Berkeley, CA, 1989) and StatView (Version 4.5, Abacus Concepts, Inc., Berkeley, CA, 1995).

We estimated standing crops of abundant species for standardized 1-ha areas of terrace fields with different cell sizes by combining areal coverages of different habitat types and mean densities of animals in these habitat types. We then compared these values with estimates of standing crop for shallow NB (from both preconstruction and reference samples) that was replaced by the terrace fields. We conducted a benefit-cost analysis of the three cell sizes using an approach similar to that described by Rozas et al. (2005a), but based on actual animal densities determined from our sample collections in 2001 and 2002. Standing crop was estimated in both September and May for brown shrimp, blue crab, and daggerblade grass shrimp *Palaemonetes pugio* Holthuis; only in September for white shrimp *Litopenaeus setiferus* (Linnaeus), pink shrimp *Farfantepenaeus duorarum* (Burkenroad), spotted seatrout *Cynoscion nebulosus* (Cuvier), bay anchovy *Anchoa mitchilli* (Valenciennes), clown goby *Microgobius gulosus* (Girard), and naked goby *Gobiosoma bosc* (Lacepède); and only in May for gulf menhaden *Brevoortia patronus* Goode, pinfish *Lagodon rhomboides* (Linnaeus) and inland silverside *Menidia beryllina* (Cope).

A base map was constructed in a Geographical Information System (GIS) from a digital georeferenced aerial image (scale = 1:14,000) taken in 2001. Areas of terrace marsh, shallow terrace pond, and borrow sites were digitized using an onscreen digitization procedure. Mean nekton densities measured in shallow open water and deeper borrow areas were combined with the relative areas of these habitat types to calculate standing crop in the open water of the different cell sizes. These values were then combined with estimates of standing crop within terrace marsh vegetation.

We used a modeling approach described by Minello and Rozas (2002) and Rozas et al. (2005a) to estimate brown shrimp, white shrimp, and blue crab populations within terrace marsh. Terrace marsh was classified into different categories based on distance to nearest shoreline using Spatial Analyst 1.1 (ESRI, Redlands, California). The overall areal coverage of each distance-to-edge category was calculated, and modeled densities for each of these categories were applied using Microsoft Excel 2000 to estimate populations of brown shrimp, white shrimp, and blue crab for each terrace cell size. These models predict densities of brown shrimp, white shrimp, and blue crab within marsh based on the densities at the vegetated marsh edge. We used densities derived from samples of the terrace marsh edge that we collected in September 2001 and May 2002. Such models are unavailable for species other than brown shrimp, white shrimp, and blue crab. Therefore, we estimated populations of these other species in terrace vegetation by multiplying the density of each species determined from our samples of terrace marsh edge by the area of marsh contained within standardized 1-ha terrace

Table 2. Comparison of nekton density and environmental conditions over shallow NB before and after restoration. Densities (mean $m^{-2} \pm 1$ S.E.) are given for the most abundant taxa collected prior to terrace construction in 1998 (n = 10) and after terrace construction in 2001–2002 (n = 7; reference area only). Only species with densities ≥ 0.5 m^{-2} are listed. Means (+ S.E.) also are given for environmental variables measured in 1998 (n = 10) and 2001–2002 (n = 7). Results of unpaired t-tests comparing means between pre- and post-construction data also are given. A p value of 0.000 indicates that probability was less than 0.005. An * indicates that the probability value was significant after alpha was adjusted as described by Rice (1989).

	1998		2001–2002			
VARIABLE	MEAN	S. E.	MEAN	S. E.	p value	
May						
Nekton Density						
Total Crustaceans	1.2	(0.4)	0.6	(0.3)	0.353	
Brown shrimp	0.6	(0.3)	0.4	(0.3)	0.665	
Total Fishes	0.5	(0.3)	0.1	(0.1)	0.392	
Environmental Conditions						
Water Temperature (°C)	25.4	(0.0)	24.5	(0.1)	0.000	*
Salinity (psu)	27.4	(0.2)	29.1	(0.4)	0.001	*
Water Depth (cm)	86.7	(5.4)	92.7	(3.8)	0.421	
Dissolved Oxygen (mg L^{-1})	5.4	(0.1)	6.1	(0.2)	0.011	
Turbidity (FTU)	14.4	(1.7)	8.0	(1.6)	0.022	
Distance to Marsh Edge (m)	65.5	(10.6)	96.1	(34.5)	0.342	
September-October						
Nekton Density						
Total Crustaceans	0.9	(0.4)	1.7	(0.5)	0.220	
White shrimp	0.6	(0.3)	0.1	(0.1)	0.338	
Total Fishes	0.7	(0.3)	4.3	(0.8)	0.000	*
Bay anchovy	0.3	(0.2)	1.3	(0.5)	0.084	
Environmental Conditions						
Water Temperature (°C)	22.1	(0.1)	28.2	(0.4)	0.000	*
Salinity (psu)	16.0	(0.3)	12.7	(0.5)	0.000	*
Water Depth (cm)	64.0	(3.3)	77.1	(6.4)	0.065	
Dissolved Oxygen (mg L^{-1})	5.7	(0.0)	6.8	(0.2)	0.000	*
Turbidity (FTU)	43.1	(2.6)	19.0	(2.0)	0.000	*
Distance to Marsh Edge (m)	77.5	(27.8)	48.1	(6.4)	0.401	

fields composed of each cell size. Although densities of most of these species within marsh vegetation are higher within the 5 m zone adjacent to open water (Minello 1999), the terraces in our study area were relatively narrow, and most emergent vegetation on these terraces was within that zone.

In estimating the cost of terrace construction, we used terrace levee length as a proxy for construction cost. For most terracing projects, project cost is determined by multiplying the total length of levees to be constructed by a fixed cost per unit length of levee (Rozas and Minello 2005a).

RESULTS

Pre-construction vs. Post-construction

Nekton densities over undisturbed shallow non-vegetated bottom (NB) were low and similar in 1998 and 2001–2002 (Table 2). The density of total fish was significantly higher in fall 2001 compared with fall 1998, but there was no consistent pattern of differences between the years. There were significant differences in water temperature and salinity between years in both spring and fall, but only the fall differences were likely to be biologically meaningful (Table 2). Turbidity was significantly higher in fall 1998 compared with fall 2001. In contrast to the densities over shallow NB, nekton density and biomass increased dramatically for many species within the terrace fields following wetland construction.

Nekton Patterns in the Terrace Fields

In post-construction samples, decapod crustaceans (74% of total) outnumbered fishes and accounted for 60% of the biomass. Five species (daggerblade grass shrimp, blue crab, white shrimp, brown shrimp, pink shrimp) made up 98% of the crustaceans we collected (Table 3).

The most abundant fishes (87% of the total) we collected included gulf menhaden, bay anchovy,

Table 3. Comparison of densities (mean $m^{-2} \pm 1$ S.E.) of the most abundant decapod crustaceans and fishes collected among treatments (small, medium, and large terrace cells and reference area) and among habitat types (marsh edge, shallow and deep nonvegetated bottom = NB) in September 2001 and May 2002. The ANOVA model used to do these analyses is shown in Table 1. A p value of 0.000 indicates that probability was less than 0.005. An * indicates that the probability value was significant after alpha was adjusted as described by Rice (1989).

	Cell Size Main Effect (n = 21)									Contrast p values		
	Small (S) Cell		Medium (M) Cell		Large (L) Cell		Reference Area (RA)		ANOVA	S Cell vs M Cell	L Cell vs M Cell	RA vs All Cells
SPECIES	MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	p value			
September 2001												
Total Crustaceans (14 species)	37.7	(12.4)	26.5	(7.3)	26.2	(8.9)	36.1	(13.6)	0.456			
Daggerblade grass shrimp	16.5	(7.1)	5.6	(2.3)	6.6	(3.1)	11.3	(4.3)	0.461			
Blue crab	6.4	(1.3)	6.6	(1.4)	9.6	(3.4)	7.6	(2.8)	0.336			
White shrimp	6.8	(2.6)	7.6	(2.6)	3.6	(1.6)	8.8	(4.6)	0.039	0.413	0.005	0.777
Brown shrimp	3.6	(1.1)	4.3	(1.5)	3.8	(1.4)	4.8	(1.6)	0.846			
Pink shrimp	2.9	(1.0)	2.4	(0.7)	2.3	(0.9)	2.3	(1.4)	0.372			
Total Fishes (21 species)	10.8	(1.6)	5.6	(1.0)	8.8	(3.4)	10.1	(3.3)	0.034	0.008	0.829	0.826
Bay anchovy	2.3	(0.9)	2.0	(0.8)	4.7	(3.2)	5.2	(3.0)	0.731			
Clown goby	3.4	(0.6)	1.6	(0.4)	2.0	(0.4)	1.3	(0.4)	0.008	0.010	0.422	0.023
Naked goby	2.1	(0.9)	1.0	(0.4)	1.1	(0.7)	0.8	(0.5)	0.090			
Species Richness	6.1	(0.6)	4.9	(0.4)	4.8	(0.4)	5.2	(0.7)	0.093			
May 2002												
Total Crustaceans (14 species)	44.6	(18.0)	14.0	(5.1)	12.7	(4.8)	17.6	(7.7)	0.026	0.045	0.932	0.050
Daggerblade grass shrimp	34.1	(15.0)	5.6	(2.7)	5.7	(3.2)	7.2	(4.4)	0.011	0.007	0.957	0.203
Brown shrimp	8.4	(2.8)	6.8	(2.1)	6.0	(2.5)	7.9	(3.1)	0.471			
Blue crab	1.5	(0.5)	1.0	(0.4)	0.8	(0.3)	1.8	(0.7)	0.197			
Total Fishes (21 species)	4.4	(1.4)	6.6	(2.7)	6.4	(2.3)	21.6	(10.7)	0.533			
Gulf menhaden	0.0	(0.0)	2.4	(2.4)	0.0	(0.0)	18.5	(10.7)	0.021	0.471	0.471	0.003
Pinfish	2.7	(1.2)	2.8	(1.0)	4.0	(1.5)	2.5	(0.7)	0.828			
Inland silverside	0.6	(0.5)	0.0	(0.0)	0.8	(0.8)	0.0	(0.0)	0.361			
Species Richness	3.1	(0.5)	2.5	(0.5)	2.5	(0.5)	2.6	(0.6)	0.323			

pinfish, clown goby, naked goby, and inland silverside (Table 3). Pinfish, gulf menhaden, spot *Leiostomus xanthurus* Lacepède, spotted seatrout, southern flounder *Paralichthys lethostigma* Jordan and Gilbert (3 individuals), striped mullet *Mugil cephalus* Linnaeus (2 individuals), and red drum *Sciaenops ocellatus* (Linnaeus) (1 individual) accounted for most of the fish biomass.

We detected few statistically significant differences in animal density or biomass among cell sizes, and none of these main effects was significant following the Bonferroni adjustment (Table 3). Without this adjustment for multiple tests, the main effect of cell size was significant for only six of 18 density tests, and no consistent pattern emerged among species. Clown goby (September) and daggerblade grass shrimp (May) densities were higher in small cells than in medium cells, whereas white shrimp (September) densities were higher in medium cells than in large cells. Gulf menhaden (May) was more abundant in the reference area than in terrace cells (i.e., all three cell sizes combined), while clown goby (September) was more abundant in terrace cells than in the reference area. When biomass was the dependent variable, the main effect of cell size was significant for three species; spotted seatrout (September) and gulf menhaden (May) had more biomass in the reference area than in terrace cells, and daggerblade grass shrimp biomass in May was greater in small cells than in medium cells.

Table 3. Extended.

Habitat Type Main Effect (n = 28)								Contrast p values		
Marsh Edge		Shallow (S)NB		Deep (D)NB		ANOVA		SNB vs DNB	Marsh Edge vs SNB + DNB	Cell Size × Habitat Type Interaction
MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	p value				p value
86.8	(9.7)	3.5	(0.5)	4.6	(0.9)	0.000	*	0.510	0.000	0.119
29.9	(5.2)	0.0	(0.0)	0.0	(0.0)	0.000	*	0.909	0.000	0.591
17.6	(2.7)	1.8	(0.3)	3.3	(0.6)	0.000	*	0.117	0.000	0.573
19.6	(3.4)	0.3	(0.1)	0.2	(0.1)	0.000	*	0.709	0.000	0.444
11.1	(1.2)	0.5	(0.2)	0.7	(0.3)	0.000	*	0.982	0.000	0.179
6.2	(1.2)	0.9	(0.3)	0.3	(0.1)	0.000	*	0.158	0.000	0.093
6.6	(1.4)	6.3	(0.8)	13.5	(3.3)	0.015		0.058	0.025	0.053
0.1	(0.1)	2.4	(0.7)	8.1	(3.2)	0.000	*	0.062	0.000	0.139
0.4	(0.1)	2.6	(0.3)	3.3	(0.5)	0.000	*	0.385	0.000	0.939
1.8	(0.8)	0.5	(0.2)	1.4	(0.5)	0.225				0.167
7.4	(0.4)	4.1	(0.3)	4.3	(0.3)	0.000	*	0.605	0.000	0.093
64.6	(12.6)	1.1	(0.2)	0.9	(0.3)	0.000	*	0.402	0.000	0.068
39.4	(11.1)	0.1	(0.1)	0.0	(0.0)	0.000	*	0.688	0.000	0.013
20.1	(2.5)	0.9	(0.2)	0.8	(0.3)	0.000	*	0.626	0.000	0.132
3.6	(0.5)	0.0	(0.0)	0.1	(0.1)	0.000	*	0.710	0.000	0.093
11.4	(1.5)	3.0	(2.0)	14.9	(8.2)	0.000	*	0.157	0.000	0.000
0.0	(0.0)	1.8	(1.8)	13.9	(8.1)	0.051				0.001
8.4	(1.1)	0.1	(0.1)	0.4	(0.2)	0.000	*	0.220	0.000	0.002
1.1	(0.7)	0.0	(0.0)	0.0	(0.0)	0.013		1.000	0.003	0.379
5.7	(0.3)	1.2	(0.2)	1.2	(0.2)	0.000	*	0.918	0.000	0.569

The mean density for most species and species richness (number of species) varied significantly among habitat types (Table 3). Daggerblade grass shrimp, brown shrimp, blue crab, white shrimp (September), pink shrimp (September), and pinfish (May) were significantly more abundant in marsh vegetation than over shallow or deep NB (Table 3, Figures 2 and 3). In addition, the 22 spotted seatrout we collected in September were present exclusively in marsh vegetation. Species richness also was higher in marsh than NB. The distribution of animal biomass among habitat types generally mirrored the patterns for density.

Significant interactions between cell size and habitat type were detected for four species (Table 3). Daggerblade grass shrimp was more abundant, and had more biomass in marsh than in open water, but means of grass shrimp density and biomass were much higher in the marsh of small cells than that of other cell size treatments (Figure 3). Pinfish also was more abundant in marsh, but differences in mean density and mean biomass between marsh and deep NB sites varied with cell size treatments. Spotted seatrout biomass was higher in marsh vegetation than over NB, but most spotted seatrout were collected in the reference marsh, and this species was not collected in the vegetation of terraces composed

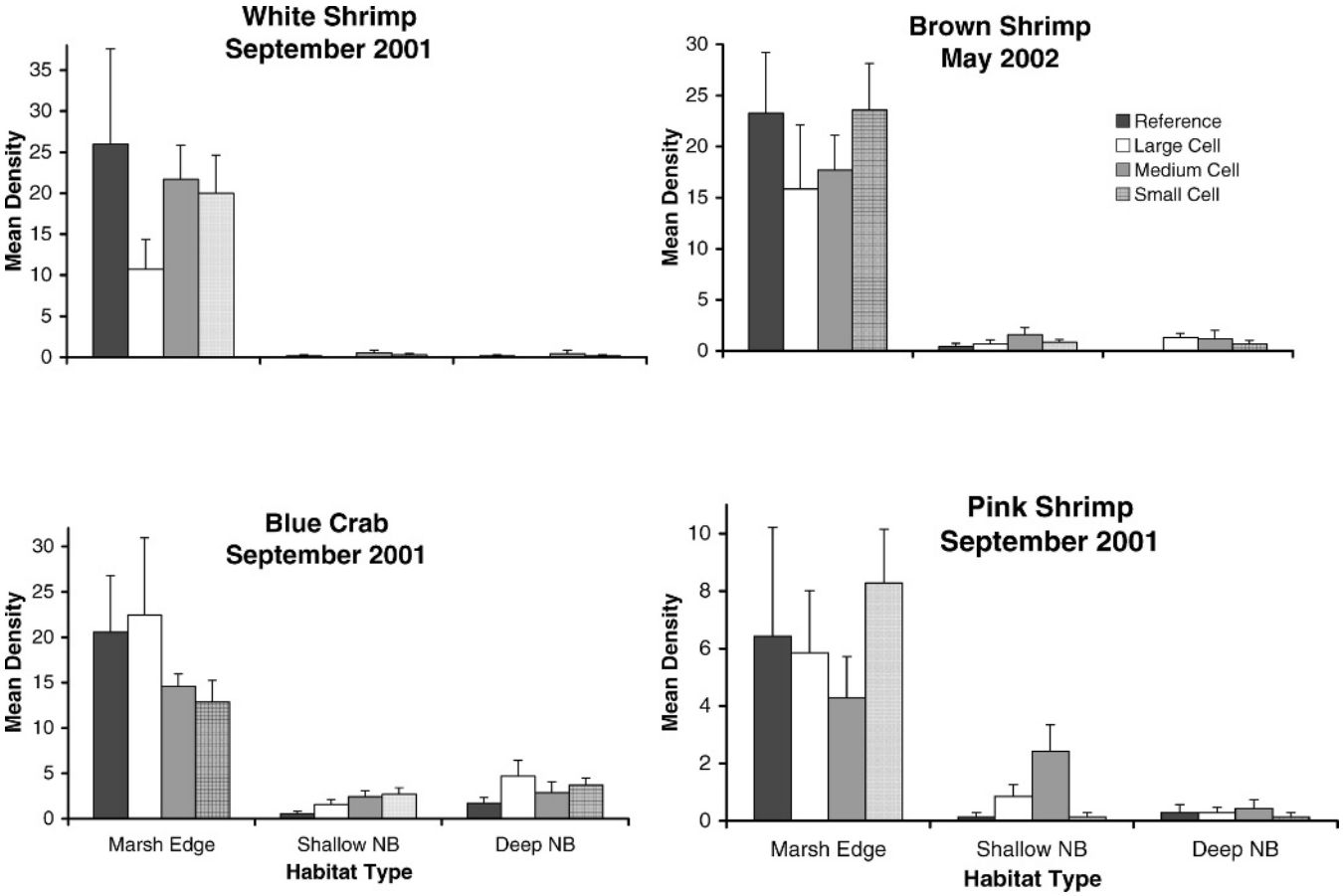

Figure 2. Comparison of mean densities (number m^{-2}, n = 7) of abundant fishery species within marsh edge vegetation, shallow nonvegetated bottom (= NB), and deep NB from terraces of three cell sizes and an adjacent natural (reference) area in September 2001 or May 2002.

of small cells. Gulf menhaden had a patchy distribution and was collected only in open water; within shallow water, it was collected only in terrace ponds of medium size cells, and within deep water, only in the reference area.

Within marsh vegetation, we observed no consistent pattern of differences in density between terrace marsh and natural marsh or among the three cell sizes (Figures 2 and 3). Marshes constructed by terracing and a nearby natural marsh appeared to support similar densities of most abundant species. Only one of the significant cell size by habitat type interactions detected in our analyses was caused by a difference in nekton density or biomass between reference and terrace marshes. Spotted seatrout biomass was higher at reference than terrace marsh sites.

Most taxa were generally not abundant over NB, and we detected no statistically significant differences in nekton densities between deep and shallow NB sites (Table 3). Total fishes, bay anchovy, and clown goby in September, however, were more abundant over NB than in marsh vegetation (Figure 3). Within terrace cells, densities of most fishery species were similar between deep borrow areas and adjacent shallow pond areas (Figures 2 and 3).

We examined the pattern of size distribution for five crustaceans among terrace cell sizes and habitat types, but detected few significant differences. Blue crabs in September were larger in marsh than NB (mean carapace width = 12.0 vs. 5.7 mm, $p < 0.001$). In May, blue crabs were collected only at marsh sites. Contrasts following significant main effects for daggerblade grass shrimp, white shrimp, and brown shrimp were not estimable because too few of these species were collected at some NB habitat types. A significant interaction between cell size and habitat type was detected for daggerblade grass shrimp in May 2002 ($p < 0.002$). The mean size of daggerblade grass shrimp within vegetation was similar among the different cell size treatments (reference = 27.8 mm, small = 29.9, medium = 28.3, large = 30.8).

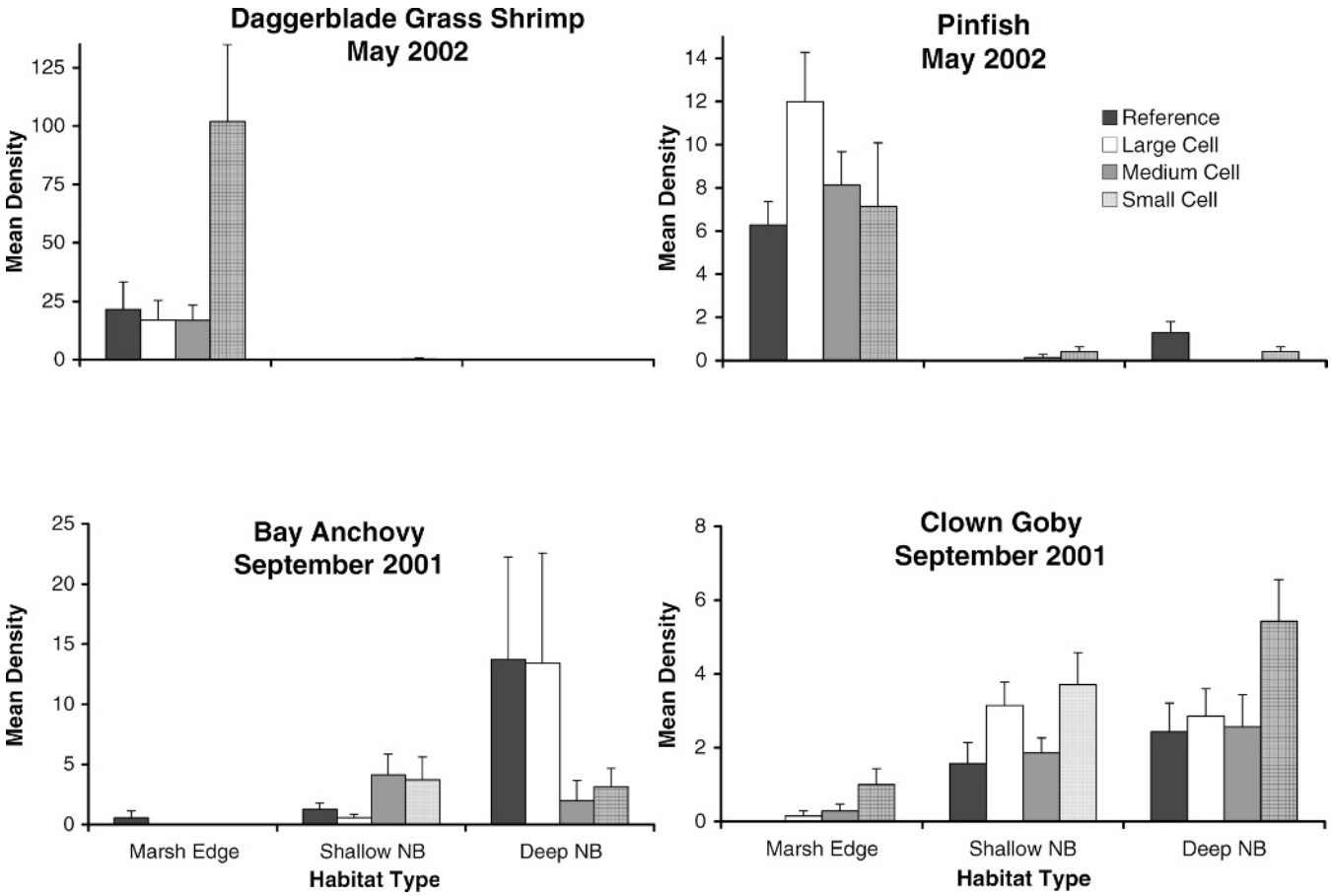

Figure 3. Comparison of mean densities (number m^{-2}, n = 7) of other abundant species within marsh edge vegetation, shallow nonvegetated bottom (= NB), and deep NB from terraces of three cell sizes and an adjacent natural (reference) area in September 2001 or May 2002.

Environmental variables differed by both cell size treatment and habitat type (Table 4). Reference sample sites were located farther from marsh shoreline than sites sampled in the terrace fields. In September, mean turbidity levels were significantly different among cell sizes, and turbidity was lowest in the small terrace cells with the least fetch. A similar pattern, however, was not apparent in May samples. Mean water temperatures (May) were higher in small and medium terrace cells compared with large cells and the reference area. This difference coincided with shallow water in small cells and the deepest water in the reference area. Mean stem density of *Spartina alterniflora* increased substantially from September 2001 to May 2002. In May, stem density was significantly higher in the reference marsh than in the terrace marsh. Other differences in physical characteristics did not appear to be biologically significant. Significant interactions between cell size and habitat type were detected for water temperature and distance to marsh edge (Table 4). Mean water temperature was similar among cell size treatments at marsh and shallow NB sites, but within deep NB sites, water temperature was lower in the reference area than within terrace borrow areas. Shallow NB sites were nearer the marsh edge than deep NB sites in terraces with small cells and within the reference area, but farther away from the marsh edge than deep NB sites in terraces with medium or large cells.

GIS and Population Analysis

The relative spatial areas of habitat types within marsh terraces differed with cell size (Table 5), and the proportions of marsh and borrow area (Deep NB) in terraces were inversely related to cell size. For example, almost 25% of small cells was borrow area, whereas only 20% of medium cells and 11% of large cells consisted of borrow area. Concurrently, the relative area of shallow NB in terraces increased with terrace size (Table 5).

Standing crop estimates of fishery species were greater within marsh terraces (regardless of cell size)

Table 4. Comparison of environmental variables (mean ± 1 S.E.) among treatments (small, medium, and large terrace cells and the reference area) and habitat types (marsh edge, shallow and deep nonvegetated bottom = NB) that we sampled in September 2001 and May 2002. The ANOVA model used to do these analyses is shown in Table 1. A p value of 0.000 indicates that probability was less than 0.005. An * indicates that the probability value was significant after alpha was adjusted as described by Rice (1989).

	Treatment Main Effect (n = 21)										Contrast p values		
Environmental Variable	Small (S) Cell		Medium (M) Cell		Large (L) Cell		Reference Area (RA)		ANOVA		S Cell vs M Cell	L Cell vs M Cell	RA vs All Cells
	MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	p value				
September 2001													
Water Temperature (°C)	27.3	(0.2)	27.8	(0.3)	27.8	(0.3)	27.6	(0.3)	0.554				
Salinity (psu)	13.2	(0.3)	13.4	(0.3)	13.9	(0.3)	12.8	(0.4)	0.082				
Water Depth (cm)	73.7	(8.8)	70.1	(9.4)	68.4	(8.3)	77.2	(8.6)	0.120				
Dissolved Oxygen (mg L^{-1})	6.5	(0.3)	6.5	(0.2)	6.5	(0.2)	6.5	(0.1)	0.980				
Turbidity (FTU)	12.2	(1.2)	18.6	(1.5)	19.7	(2.0)	18.9	(1.4)	0.002	*	0.004	0.566	0.242
Distance to Marsh Edge (m)	2.7	(0.4)	8.9	(1.7)	11.5	(2.9)	79.5	(20.2)	0.000	*	0.377	0.711	0.000
Stem Density (stems m^{-2})	91.1	(19.1)	108.0	(11.2)	109.4	(27.2)	109.1	(23.7)	0.911				
May 2002													
Water Temperature (°C)	25.6	(0.4)	25.6	(0.5)	24.8	(0.5)	24.1	(0.6)	0.000	*	0.819	0.014	0.000
Salinity (psu)	29.4	(0.3)	29.4	(0.4)	29.7	(0.3)	28.9	(0.3)	0.281				
Water Depth (cm)	74.0	(7.4)	82.3	(7.0)	82.7	(6.2)	85.1	(8.4)	0.010		0.017	0.918	0.055
Dissolved Oxygen (mg L^{-1})	7.1	(0.2)	7.0	(0.2)	6.6	(0.2)	6.8	(0.2)	0.149				
Turbidity (FTU)	9.6	(1.8)	8.2	(0.8)	10.7	(1.2)	12.1	(2.5)	0.393				
Distance to Marsh Edge (m)	2.4	(0.4)	7.9	(1.6)	11.9	(3.2)	97.3	(21.2)	0.000	*	0.543	0.654	0.000
Stem Density (stems m^{-2})	208.4	(21.6)	204.1	(19.4)	204.9	(39.2)	330.4	(49.9)	0.042		0.932	0.989	0.005

than over shallow NB (Table 6, Figure 4). Blue crab, white shrimp, brown shrimp, and pink shrimp were at least 7, 1.6, 3, and 10 times more abundant, respectively, in the marsh terraces (Table 6). Gulf menhaden and spotted seatrout were collected in at least some samples taken within the terraces, but not over shallow NB in the reference area or during preconstruction sampling. Most abundant forage species also were more abundant within marsh terraces than over shallow NB.

Based on our modeling estimates, populations of brown shrimp, white shrimp, blue crab, and most other species increased as cell size decreased (Table 6, Figure 4). The cost of terrace construction (estimated by terrace levee length), however, increased much faster than the population size of fishery species as cell size decreased (Table 5, Figure 4). Based on our analysis, terrace fields constructed of medium cells would be more cost effective than terrace fields composed of either small or large cells for brown shrimp, white shrimp, or gulf menhaden (Table 6). Terrace fields composed of large cells appear to be most cost effective for blue crab, and terrace fields of medium or large cells may be more cost effective than those composed of small cells for pink shrimp and spotted seatrout (Table 6). When we combined all of these fishery species in our analysis, terraces composed of medium and large cells ranked higher in cost effectiveness than small cells (Figure 4). Note that as cell size decreases, the standing crop of all abundant species combined (all species, Table 6) increases at a much faster rate than

Table 4. Extended.

Habitat Type Main Effect (n = 28)								Contrast p values		Cell Size × Habitat Type Interaction
Marsh		Shallow (S)NB		Deep (D)NB		ANOVA		SNB vs DNB	Marsh Edge vs SNB + DNB	
MEAN	S. E.	MEAN	S. E.	MEAN	S. E.	p value				p value
27.8	(0.3)	27.8	(0.2)	27.3	(0.2)	0.230				0.026
13.9	(0.3)	13.3	(0.3)	12.8	(0.3)	0.008		0.178	0.005	0.098
26.1	(1.9)	73.4	(2.6)	117.6	(2.6)	0.000	*	0.000	0.000	0.628
6.8	(0.2)	6.5	(0.2)	6.2	(0.1)	0.068				0.293
13.5	(1.1)	16.7	(1.2)	22.4	(1.5)	0.000	*	0.001	0.000	0.255
0.8	(0.0)	24.1	(3.7)	52.0	(16.7)	0.000	*	0.000	0.000	0.000
104.4	(10.1)	0.0	(0.0)	0.0	(0.0)					
27.2	(0.2)	25.6	(0.2)	22.3	(0.2)	0.000	*	0.000	0.000	0.010
29.6	(0.3)	29.4	(0.2)	28.9	(0.2)	0.164				0.483
42.3	(1.8)	83.4	(1.8)	117.4	(3.0)	0.000	*	0.000	0.000	0.186
7.3	(0.1)	6.5	(0.2)	6.8	(0.1)	0.000	*	0.238	0.000	0.260
13.7	(2.0)	8.8	(1.0)	8.1	(0.9)	0.012		0.735	0.003	0.682
1.0	(0.1)	34.6	(10.9)	54.0	(16.0)	0.000	*	0.014	0.000	0.000
237.0	(19.5)	0.0	(0.0)	0.0	(0.0)					

that of fishery species alone (Figure 4). This rate of increase for all nekton combined is comparable to the rate of increase for the cost of terrace construction. Therefore, if the standing crop of all nekton combined was used to assess cost effectiveness, small cells would rank first, medium cells second, and large cells third (i.e., cost effectiveness would increase as cell size decreases).

Table 5. Results of habitat classification for terraces composed of small, medium, and large cells. The standardized levee lengths given here were estimated by determining the total length of levees within hypothetical 1-ha terrace fields composed of cells for each cell size.

Cell Size	Marsh Area (m^2)	Shallow Pond Area (m^2)	Borrow Area (m^2)	Total Area (m^2)	Levee Length (m ha^{-1})
Small	324.6 (35.3%)	367.2 (39.9%)	228.3 (24.8%)	920.1	491
Medium	1,106.1 (27.6%)	2,115.2 (52.9%)	780.3 (19.5%)	4,001.6	267
Large	1,951.3 (13.1%)	11,280.2 (75.7%)	1,675.2 (11.2%)	14,906.7	149

Table 6. Comparison of standing crops among terraces composed of small, medium, and large cells, reference area (2001–2002 data), and preconstruction site (1998 data). Standing crops (number ha^{-1}) and benefit-cost ratios are standardized to a hypothetical 1-ha terrace field for each cell size and 1-ha of shallow NB for reference and preconstruction areas. The benefit:cost was derived by first subtracting the reference area standing crop for that species and cell size and then dividing by the standardized levee length given in Table 5.

	Standing Crop					Benefit:Cost (Standing Crop per Levee Length)		
	Small Cell	Medium Cell	Large Cell	Reference Area	Preconstruction	Small Cell	Medium Cell	Large Cell
White shrimp	55,044	46,463	9,537	1,430	6,000	109	169	54
Brown shrimp	46,694	33,561	17,101	5,715	3,000	83	104	76
Blue crab	35,120	28,131	20,788	2,850	1,500	66	95	120
Pink Shrimp	29,931	24,361	14,442	1,430	0	58	86	87
Spotted Seatrout	0	1,642	558	0	0	0	6	4
Gulf menhaden	0	40,802	0	0	0	0	153	0
Fishery species above combined	166,789	174,960	62,426	11,425	10,500	316	612	342
Daggerblade grass shrimp	265,859	38,607	23,864	1,430	0	539	139	151
Pinfish	27,789	19,530	15,600	0	2,000	57	73	105
Bay Anchovy	22,714	27,401	19,112	12,860	3,000	20	54	42
Inland Silverside	5,999	329	3,158	0	0	12	1	21
Clown goby	31,929	16,456	27,215	15,710	0	33	3	77
ALL NEKTON	521,079	277,283	151,375	41,425	15,500	977	883	738

DISCUSSION

The Galveston Island State Park has been losing wetlands to shallow open water, and marsh terracing has been used to restore lost wetland habitat. Based on our nekton density and population estimates, this restoration technique has successfully improved fishery habitat. Brown shrimp were 3–8 times more abundant in the terrace fields (depending on terrace cell size) than before restoration. White shrimp and blue crab were 1.6–9 and 7–12 times more abundant, respectively, after restoration. Our conclusion is consistent with an earlier study that assessed and compared several restoration projects, including this one, in Galveston Bay (Rozas et al. 2005a). The previous study, which employed GIS and a modeling approach to assess fishery support, concluded that marsh terracing was the most cost-effective restoration method analyzed because the technique creates a relatively high proportion of marsh edge that supports high densities of fishery species, and marsh terraces are relatively inexpensive to construct (Rozas et al. 2005a). Other studies comparing densities of nekton between sites restored by marsh terracing and pre-restoration conditions draw similar conclusions (Rozas and Minello 2001, Bush Thom et al. 2004, Gossman 2005, La Peyre et al. 2007).

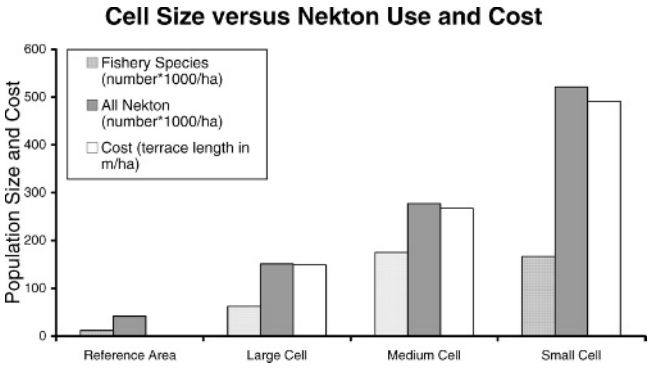

Figure 4. Relationship among terrace cell size, nekton use, and cost. Population size (individuals × 1000) for all fishery species (white shrimp, brown shrimp, blue crab, pink shrimp, spotted seatrout, gulf menhaden) and all nekton (fishery species plus daggerblade grass shrimp, pinfish, bay anchovy, inland silverside, clown goby) is plotted for standardized 1-ha areas of terrace field composed of each cell size and shallow NB reference area. Cost of terrace construction (estimated by terrace levee length) also is plotted for each cell size.

Nekton use of the shallow nonvegetated bottom where the terraces were built differed slightly between the pre- and post-construction (reference area) periods. In particular, fish densities were higher in fall 2001 than in 1998. These differences may be attributable to annual variability in nekton populations that can often be substantial (Rozas et al. In press). Also, various significant differences in environmental characteristics (e.g., temperature, salinity, and turbidity) may have contributed to any

differences in nekton abundance between years. Construction of the restoration project also may have modified the surrounding bay bottom and environmental conditions in the study area. Disturbance of sediment during terrace construction may have altered nearby sediment composition, or the installation of protective wave barriers around the site may have contributed to environmental changes. For example, the presence of terraces and wave barriers decreased fetch across the study area and may have decreased wave energy and contributed to the lower turbidity levels we observed in post-construction samples. Regardless, replacing shallow NB in the study area with marsh terraces appeared to benefit fishery species based on a comparison of populations before and after restoration.

We observed few differences in densities or biomass attributed to terrace cell size based on fine-scale (m^2) measurements from field sampling. Densities and biomasses of fishery species in the three different habitat types were similar among cell sizes. However, when we combined these densities with areal coverages of habitat types to calculate standing crop at a larger spatial scale, populations of some species appeared to differ among terrace cell sizes. Standing crops of species closely associated with emergent vegetation generally increased as terrace cell size decreased (Rozas and Minello 2001, Rozas et al. 2005a), and small cells supported higher densities of most fishery species than large cells. Terrace fields composed of medium or large cells, however, afforded the greatest habitat benefit for fishery species per unit construction cost. Our benefit-cost analysis shows that terrace fields constructed of medium or large cells would be much more cost effective for restoring fishery habitat than terrace fields composed of small cells. Rozas et al. (2005a) concluded that terraces constructed of medium cells were most cost effective. In their study, populations of three fishery species (brown shrimp, white shrimp, blue crab) were modeled to determine benefits, and all three populations were combined in the analysis. When we combined six fishery species in our analysis, terrace fields composed of large or medium cells were comparable in cost effectiveness and more cost effective than terrace fields composed of small cells. Interestingly, had this analysis been based on the entire nekton assemblage, terrace fields with small cells would have been ranked first in cost effectiveness because, as cell size decreased, the standing crop of all nekton combined increased at about the same rate as the cost of terrace construction.

Within terrace ponds, we found little difference in habitat value between deep borrow areas and adjacent shallow portions of terrace cells. Other studies have shown that nekton densities often decrease with increasing water depth. Most of the abundant fishes in nearshore areas of Barataria Bay, Louisiana were associated with shallow water (Baltz et al. 1993). Juvenile blue crab, naked goby, and daggerblade grass shrimp within pipeline canals also are more abundant in shallow (< 1 m) than deep (≥ 1 m) areas (Rozas and Reed 1994). Densities of grass shrimp and killifish in Chesapeake Bay are significantly greater at depths < 36 cm than in deeper water (Ruiz et al. 1993). We hypothesized that deep borrow areas might provide a refuge for large aquatic predators that do not occur in shallow water (Ruiz et al. 1993, Paterson and Whitfield 2000), and the presence of these predators would reduce densities of vulnerable species through avoidance or predation (McIvor and Odum 1988, Dittel et al. 1995). The lack of a depth effect in our results may have been related to the close proximity of emergent vegetation to the deep borrow areas. Access to protective emergent vegetation during flooding tides may increase the habitat value of deep borrow areas in the terrace fields.

Terrace ponds were also the focus of a recent study assessing the value of habitat created by marsh terracing in southwest Louisiana (Gossman 2005, La Peyre et al. 2007). When compared with pre-restoration conditions, terrace ponds were found to improve nekton habitat, but La Peyre et al. (2007) concluded that these terrace ponds lacked functional equivalency with natural marsh ponds. Their conclusion was based on differences in nekton assemblages between terrace and reference ponds and the poorer condition of some fishes (sailfin molly *Poecilia latipinna* (Lesueur) and clown goby) collected from the terrace ponds in their study. Future research to examine the efficacy of restoring habitat with marsh terracing likewise should incorporate multiple indicators of habitat value into the study design. Information on growth and survival rates for fishery species would be especially useful. This information could be used with density and biomass data to estimate fishery productivity, and estimates of productivity may provide the best indicator of habitat value in such assessments.

We did not observe differences in densities between constructed terrace marsh and a nearby natural (reference) marsh for most species commonly associated with marsh vegetation. Unlike Rozas and Minello (2001), who reported higher densities of brown shrimp and blue crab in natural marsh than marsh constructed by terracing, we observed similar densities of brown shrimp and blue crab between

these marsh types. Marshes in Galveston Bay built from dredged material reach maximum habitat support just after 1 yr from construction (Minello 2000), but comparisons of natural and constructed (3–15 yr old) salt marshes in Galveston Bay and elsewhere in Texas show that densities of fishery species can be significantly reduced in created marshes (Minello and Zimmerman 1992, Minello and Webb 1997). Only the pattern we observed in our study for spotted seatrout was consistent with such a conclusion.

Our analysis detected few clear differences in the size of organisms among either terrace cell size or habitat type. In fall, blue crabs were significantly larger at vegetated marsh sites than over nonvegetated bottom. A similar pattern of larger blue crab in marsh than over NB also has been documented for other locations in Texas (Thomas et al. 1990, Rozas and Minello 1998) and Louisiana (Castellanos and Rozas 2001, Rozas et al. 2005b, Rozas and Minello 2006). In a study of marsh terraces at SNWR, Louisiana, white shrimp were significantly larger in a nearby reference marsh than on marsh terraces (Rozas and Minello 2001), but we observed no such pattern in our study.

In sum, our analysis showed that constructing marsh terraces improved fishery habitat in comparison to the shallow nonvegetated bottom present before construction. Our conclusion is consistent with an earlier assessment of restoration methods used in Galveston Bay (Rozas et al. 2005a) and other studies of marsh terracing projects in Louisiana (Rozas and Minello 2001, Bush Thom et al. 2004, Gossman 2005, La Peyre et al. 2007). A landscape-scale analysis of terrace cell size revealed that although small cells supported higher populations of nekton, terrace fields constructed of medium or large cells would be more cost-effective in providing fishery habitat. This result was not apparent from our initial analysis of small-scale measurements of density and biomass. Overall, animal densities and biomasses were low over nonvegetated bottom, and the habitat value of deep borrow areas and adjacent shallow terrace ponds appeared similar.

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